Equilibrium model of the ferrosilicon melting process in the submerged arc furnace.

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Abstract **It has been presented a model that simulates of the ferrosilicon smelting process in submerged arc furnace. The model is a system of two closed isothermal reactors: the upper one with lower temperature T_1, and the lower one with the higher temperature T_2 among which there is exchange of mass cyclically. In calculations has been used algorithm of the Gibbs Free Energy Minimization Method and the new opportunities created by the HSC 6.1 software package. The HSC 6.1 include additive functions that enable to use of thermochemical database and equilibrium calculations directly on the Excel spreadsheet. . It has been made balance of heat and mass transfer of the process and it has been presented relations between process temperature conditions, and exchange of mass in the reaction Fe-Si-O-C-Al-Ca-Mg-Ti system. On the base of model it has been identified technical and economic indices of the process.**

Keywords **ferrosilicon process, submerged arc furnace, FEM model**

I. INTRODUCTION

For a fixed composition of the initial reaction mixture and set conditions of temperature and pressure $(T, P = const)$ the composition of the equilibrium system is the most stable and corresponds to the minimum Gibbs Free Enthalpy. Non- stoichiometric algorithm of the Gibbs Free Energy Minimization Method (FEM) reduces to solving of the nonlinear optimization problem with the constraints of mass balance of individual elements constituting the system in which the objective function is:

$$\min_{\boldsymbol{n}} \frac{G(T,P,\boldsymbol{n})}{RT} \qquad (1)$$

where:

$G(T,P,\boldsymbol{n})$ – Gibbs free enthalpy function,

$\boldsymbol{n} = (\boldsymbol{n}^1, \boldsymbol{n}^2, \dots, \boldsymbol{n}^f)$,

$\boldsymbol{n}^r = (n_1^r, n_2^r, \dots, n_{k^r}^r)$

$\boldsymbol{n}^r$ - vectors whose elements are the number of moles components of the various phases of r, $r = 1,2,\dots,f$,

f – number of phases constituting the system,

R - gas const.

This algorithm requires the delivery of input data as the initial reaction mixture composition, parameters of the process (T, P) and list of ingredients that may arise in the composition of equilibrium phases.

This approach does not specify the chemical reactions, or stoichiometric equations. With the spread of software to solve the FEM problem analysis of the thermodynamic carbon reduction of silica has been the subject of many publications [3]-[4]. New opportunities creates to incorporate to the HSC 6.1 thermochemical software that allows to use thermochemical database and resolve the FEM problems directly in an Excel spreadsheet.

II. MODEL OF THE FERROSILICON PROCESS

Based on the FEM algorithm, it has been presented a model of the reaction zones lacated around electrodes tips in the ferrosilicon submerged arc furnace. The model is a system of two closed isothermal reactors: the upper one with lower temperature T_1, and the lower one with the higher temperature T_2 (Fig. 1). Between the reactors and the environment, and between the reactors takes place inside the system periodically exchange mass in the moments when the reactors reached a steady state. Condensed products of chemical reactions move from top to bottom, and gas phase components in the opposite direction.

Simulation of the a continuous process of smelting ferrosilicon it has been implemented recursively. In subsequent cycles a portion of the reactants are introduced to the upper reactor. The molar composition of reaction mixture is approximately equivalent to the batch mixture of raw materials for the ferro-silicon smelting process:

$$\left.\begin{array}{l} SiO_2 + 1.89C + 0.14Fe + 0.015Al_2O_3 + \\ + 0.008CaO + 0.003MgO + 0.0001TiO_2 \end{array}\right\} \qquad (2)$$

At the same time gas products leave the reactor 1 , which after cooling to a temperature of 850 ^{0}C do not participate in the further process, and the reactor 2 leave condensed products which forming a metallic and slag phases. In addition, the products of condensed phases of reactor 1 pass into the reactor 2, where in the next cycle are involved in reactions, and gaseous products from the reactor 2 pass to reactor 1, where are condensed.

The resulting of process condensation condensed phases components are back again to the reactor 2 and are involved in the reactions in the next cycle. By using the HSC 6.1 thermochemical database it was found that in the temperature range from 1500 to 2700 ^{0}C may occur five phases in the Fe-Si-O-C-Al-Ca-Mg-Ti system. In view of the large number of components in Table 1 shows the

components of the various phases of limiting itself to the Fe-Si-O-C system. It can be assumed that in model the reactor 1 corresponds to the charge zone of submerged arc furnace in which heat is produced on the principle of resistive heating, and the reactor 2 corresponds to zones of the furnace in which heat is produced by electric arc. The model is a development of earlier models and concepts presented in the literature [2] - [4]. Using macros developed themselves in Excel Visual Basic it has been conducted a series of simulation calculations on a spreadsheet and it has been made the heat and material balance of the process.

TABLE I

COMPONENTS OF VARIOUS PHASES OF FE-SI-O-C SYSTEM.

Faza1	C(g)	C_2(g)	C_3(g)	C_4(g)	C_5(g)	C_{60}(g)	CO(g)
	CO_2(g)	C_3O_2(g)	Fe(g)	Fe_2(g)	$Fe(CO)_5$(g)	FeO(g)	FeO_2(g)
	O(g)	O_2(g)	C_2O(g)	O_3(g)	Si(g)	Si_2(g)	Si_3(g)
	Si_4(g)	SiC(g)	SiC_2(g)	Si_2C(g)	SiO(g)	SiO_2(g)	Si_2O_2(g)
Faza2	$FeCO_3$	$Fe(CO)_5$	$Fe_2(CO)_9$	$Fe_3(CO)_{12}$	$Fe_{0.945}O$	$Fe_{0.947}O$	FeO
	$FeO_{1.056}$	Fe_2O_3	Fe_3O_4	$FeO*SiO_2$	$2FeO*SiO_2$	$FeSiO_3$	
	SiO_2						
Faza3	C						
Faza4	SiC						
Faza5	Fe_3C	Fe	FeSi	$FeSi_2$	$FeSi_{2.33}$	$FeSi_{2.43}$	Fe_3Si
	Fe_5Si_3	Si					

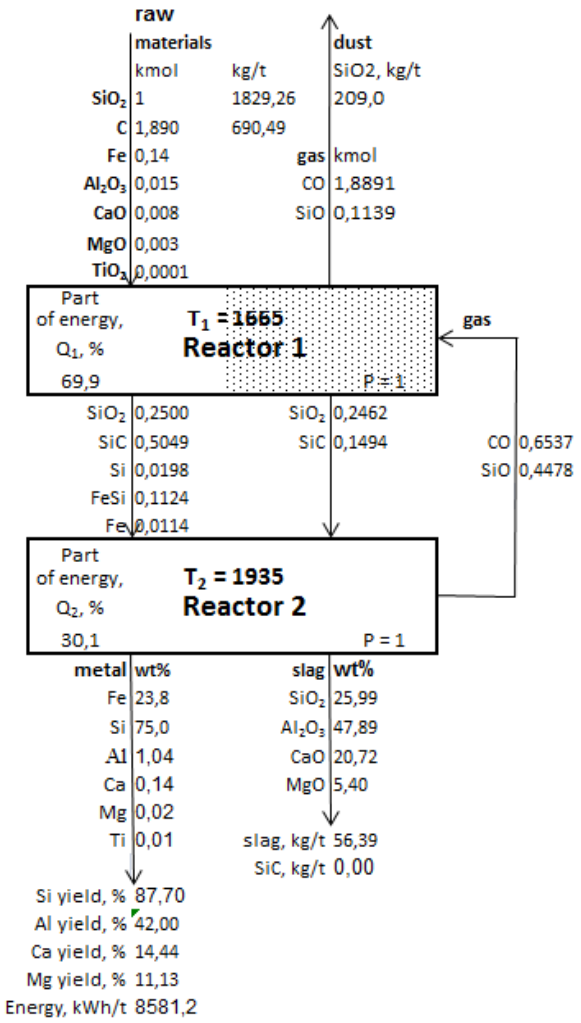

Fig. 1. The results of calculations for physic-chemical model of the ferrosilicon process with two isothermal reactors after 50 cycles. System Fe-Si-O-C-Al-Ca-Mg-Ti, temperature of the reactor 1 , T_1 = 1665 ℃.

Fig.1 shows the results of calculations for the temperature T_1 = 1665 ^{0}C corresponding to the process after 50 cycles. The temperature of the reactor 2 is the temperature at which the Si yield of the metallic phase is a maximum for a given temperature T_1. In the reactor 1 taking place mainly processes of SiC formation by reaction of silica with carbon and reactions condensation of SiO gas oxide. In the reactor 2 taking place processes of SiO gas generation and silicon metal production by reduction of silica with SiC carbide.

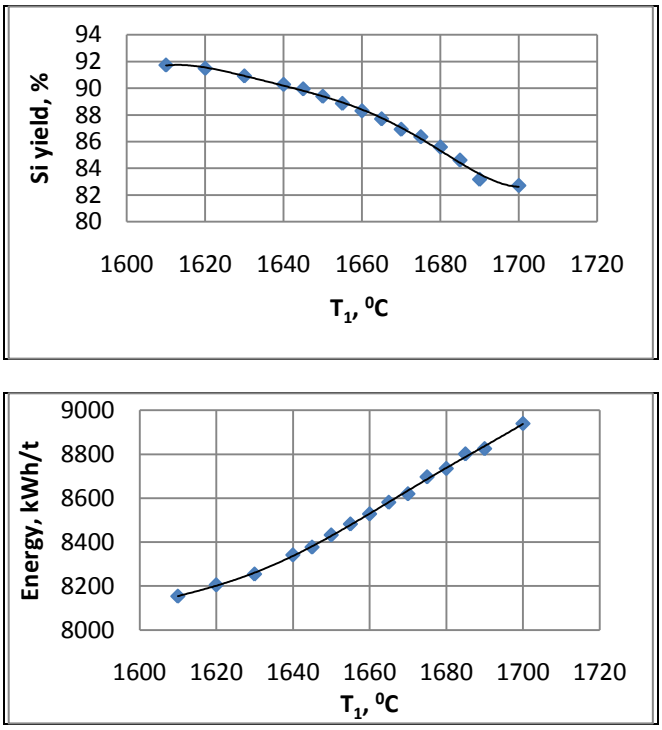

Fig. 2. Effect of reactor temperature T_1 on the Si yield end specific energy consumption in the process.

III. CONCLUSION

Calculation results for the material and heat balance obtained by the model shows good agreement with real results in industrial conditions. Significant impact on the efficiency of the reduction process are the temperature conditions. Fig. 2 shows the relationship between the temperature T_1 of the reactor 1, and a yield of Si and specific energy consumption.

IV. ACKNOWLEDGEMENTS

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